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Final Report

Advanced Gas Phase Reactor for Growth of Ge_xSi_{1-x}
Grant AFOSR-89-0144

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ABSTRACT

We have designed and constructed a reactor for the growth of Ge_xSi_{1-x} films by the newly developed technique of UHV/ CVD epitaxy. Films of varying germanium content have been successfully grown and characterized at temperatures as low as 577 C. Work is in progress with respect to optimization of the wafer cleaning procedure and studies of dopant incorporation and device fabrication will be initiated in the near future.

Introduction

This project was intended to explore the use of a new growth technique, UHV/ CVD epitaxy, for growth of Ge_xSi_{1-x} epitaxial strained layers on silicon substrates. Strained layers of Ge_xSi_{1-x} are of considerable interest for possible applications in heterojunction bipolar transistors and other advanced devices. The UHV/ CVD technique has major advantages over other growth techniques such as MBE and limited reaction processing (LRP) but has not yet been used outside of IBM. To a large degree, this is because the details of the reactor construction have been closely held within IBM. In the course of this project, we have completed construction of our epitaxial reactor and have successfully grown Ge_xSi_{1-x} layers with a range of temperatures and germanium concentrations.

Our major accomplishments to date are as follows:

1. The first demonstration of growth of epitaxial Ge_xSi_{1-x} by the UHV/ CVD technique outside of IBM.

2. Completion of a study of growth rates of epitaxial and polycrystalline material over a range of temperatures (577- 665 C) and germanium contents.

3. The first detailed description of the construction and operation of a UHV/ CVD growth system (submitted for publication).

4. Initial characterization of the undoped films with respect to germanium and oxygen contents and microstructure.

Details of these s are available in publications which have been submitted or which will be submitted in the near future. Papers which have already been submitted for publication are attached to this report (Appendices I- III).

In addition, the availability of this growth system has led to the development of a number of collaborations with other institutions or investigators. Below we describe briefly the nature of the collaborations, a brief summary of the results to date, and a description of future plans.

Collaborations with other Investigators

HBT Fabrication and Microstructure Studies

(Prof. M.K. Hatalis, Department of Electrical and Computer Engineering, Lehigh University, Bethlehem, PA).

This collaboration involves both microstructural studies of Ge_xSi_{1-x} layers by TEM and the fabrication of devices. Films grown at CMU have been studied in planar section and the results confirm that the material is indeed epitaxial. Based on a small number of samples, the defect density is quite low in Ge_xSi_{1-x} samples but a significant number of stacking faults and dislocations are observed in pure silicon epitaxial layers. A paper on this work has been submitted for the Spring MRS Meeting (see list below). This study will be expanded to include material deposited at different temperatures and under different conditions. With respect to device fabrication, a mask set suitable for two different HBT processes has been designed and is now being fabricated. It is planned that

devices will be fabricated using a mesa etch process at Lehigh and using an ion implanted process at CMU.

Photoluminescence of Ge_xSi_{1-x}

(Prof. T.E. Schlesinger, Department of Electrical and Computer Engineering, Carnegie Mellon University)

Photoluminescence has been observed from Ge_xSi_{1-x} films grown in our system and the band gap deduced from the peak positions is in reasonable agreement with that expected based on the germanium content. We are now planning additional experiments. We expect to use photoluminescence as a measure of film quality. In addition, studies of quantum well structures are being considered for the future.

Rutherford Back Scattering

(Dr. Ir. Aart A. van Gorkum, Philips Research Laboratories, Eindhoven, The Netherlands)

The group of van Gorkum at Philips is active in the growth of Ge_xSi_{1-x} by MBE. They have agreed to characterize some samples of ours by RBS which will provide a quantitative measure of film perfection and also a check on our measurements of germanium content. One set of samples has been sent already and we are awaiting results.

Secondary Ion Mass Spectroscopy

(Dr. T.I. Kamins and Mr. J. Turner, Hewlett Packard Laboratories).

SIMS measurements have been performed in order to provide another measure of germanium content and also to study oxygen content and the interfacial abruptness. Observed germanium content is in good agreement with our measurements by x-ray diffraction. The measurements of oxygen content were most interesting. The oxygen content in the bulk of the films was below the instrumental background (5×10^{18} cm^{-3} at the time these measurements were done). This is considerably below the oxygen content in material grown by limited reaction processing ($\approx 10^{20}$ cm^{-3}). However, a large oxygen peak was observed at the epitaxial layer- substrate interface. Combined with our observation of a growth incubation time, this led us to the conclusion that the surface was not completely clean before growth was initiated. We have identified a number of possible techniques for improved surface cleaning which are compatible with UHV/ CVD growth, and a study of these is presently under way. We plan to provide additional samples for SIMS after these studies are completed.

Future Research Plans

At Carnegie Mellon, our work in the near future will focus first on the evaluation of improved techniques for surface cleaning. Several possible changes in our cleaning procedure are planned based on previous published work. We are confident that these changes will result in a considerable decrease in the amount of interfacial oxygen. We plan to begin growth of doped films

in the very near future. Studies of dopant incorporation, particularly of n type dopants, will be a major focus. Finally, device studies are expected to begin in the this year as doped films of high quality become available.

Since beginning of this project in December, 1988, we have made rapid progress with respect to the growth of Ge_xSi_{1-x} using this new technique. Reports in the literature since then have shown increasing research efforts on Ge_xSi_{1-x} HBTs and devices with impressive performance are now being reported by several groups. As we predicted in our initial proposal, IBM has successfully applied this technique to the fabrication of HBTs with excellent performance. We are now poised to join in the further development of this important growth technique and its application to advanced semiconductor devices.

Publications, Conference Presentations, and Seminars

Publications

"Growth and Characterization of Epitaxial Ge_xSi_{1-x} using UHV/ CVD," D.W. Greve and Marco Racanelli, (to appear in *Proceedings of the Sixth Silicon Symposium* Montreal, Canada).

"Temperature Dependence of Growth of Ge_xSi_{1-x} by UHV/ CVD Epitaxy," Marco Racanelli and D.W. Greve, (submitted to *Applied Physics Letters*).

"Construction and Operation of a UHV/ CVD Epitaxial Reactor for Growth of Ge_xSi_{1-x}," D.W. Greve and Marco Racanelli, (submitted to the *Journal of Vacuum Science and Technology*).

Conference Presentations

"Growth and Characterization of Epitaxial Ge_xSi_{1-x} using UHV/ CVD," D.W. Greve and Marco Racanelli, (to be presented at the 1990 Electrochemical Society Spring Meeting, Montreal, Canada).*

"Structural Characteristics of Silicon and Silicon- Germanium Epitaxial Layers Grown by a New UHV/ CVD System," F. Lin, M.K. Hatalis, Marco Racanelli, and D.W. Greve, (submitted to the 1990 MRS Spring Meeting).

"Growth of Epitaxial Layers of Ge_xSi_{1-x} by UHV/ CVD," Marco Racanelli and D.W. Greve, (submitted to the 1990 MRS Spring Meeting).

*Also appears under *Publications*

Seminars

"Ge_xSi_{1-x} Heterojunction Bipolar Transistor: Performance Potential and Growth Technology," Kodak Corporation, Electronic Research Laboratory, Rochester, NY (August 10, 1989).

"Silicon- Based Heterojunctions and Devices- Growth and Applications," Department of Electrical Engineering, Tampere University of Technology, Tampere, Finland (October 4, 1989).

"Silicon- Based Heterojunctions and Devices- Growth and Applications," IMEC, Leuven, Belgium (November 16, 1989).

"Silicon- Based Heterojunctions and Devices- Growth and Applications," Philips Research Laboratories, Eindhoven, the Netherlands (November 17, 1989).

"Silicon- Based Heterojunctions and Devices- Growth and Applications," Department of Physics and Measurement Technology, Linköping University, Linköping, Sweden (November 27, 1989).

"Silicon- Based Heterojunctions and Devices- Growth and Applications," AEG Aktiengesellschaft, Forschungsinstitut, Ulm, Germany (November 30, 1989).

"Growth and Applications of Ge_xSi_{1-x} on Si," Department of Chemistry, Helsinki University of Technology, Helsinki, Finland (December 8, 1989).

"Faster than Silicon: Prospects for Ge_xSi_{1-x}/ Si Heterojunction Bipolar Transistors," Department of Electrical and Computer Engineering, Carnegie Mellon University, (February 1, 1990).